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A Method for Determining the Probability of Vehicle Overturn in Nuclear Engagements

by John S. Wicklund

U.S. Army Electronics Research
and Development Command
Harry Diamond Laboratories
Adelphi, MD 20783

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Vehicular overturn can be a significant factor in a tactical nuclear battlefield by restricting mobility or firepower at crucial times. A method for calculating overturn relates the probability of overturn to easily calculated blast parameters. Tables permit computation of overturn probability for several U.S. tracked vehicles, the Russian ZSU, and a U.S. truck with communica-

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tion shelter. The method can be extended to compute overturn probabilities for arrays of vehicles used in small tactical units.

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1. INTRODUCTION

The importance of the overturn of vehicles on a tactical battlefield is often underestimated by analysts. Experience gained in conventional wars and maneuvers indicates that overturn rarely results from enemy action; the more usual contributing factors are terrain and driver error. Moreover, overturn has most often occurred with lighter vehicles like jeeps, which are easily righted by a small crew of men. The rare overturned heavy vehicle requires a crane, but one is usually available, and the vehicle can be righted in less than an hour. Cargo is usually salvageable; even electronic equipment mounted in racks in truckborne communications shelters has survived tests in which the trucks were manually tipped over. Conceivably, a radio attached to a jeep might be broken, but the impact of overturn on command, control, and communications seems minimal.

This underestimation has carried into nuclear warfare. One well-known guide[1] categorizes overturn as the first stage of "moderate" damage, which is just a little more serious than "slight" damage. Taken by itself, "moderate" is a just evaluation. As a consequence, most planners do not consider a vehicle killed until "severe" damage--such as breaking of a drive train--is sustained.

Such a view ignores the realities of a battlefield situation. A local commander might be able to cope with the inconvenience of one overturned M113 personnel carrier, but the situation is acute if five out of six of his M113's are upside down. Presumably, the nuclear weapon has been dropped as an opening round for offensive action: enemy armored and mechanized infantry units can be expected on the scene shortly. The local commander can neither maneuver nor withdraw in good order. Such damage *cannot* be considered moderate (except, possibly, by the enemy, who can easily salvage the overturned vehicles once the situation has restabilized).

Vehicle overturn must be taken in a tactical context if detailed war-gaming is to be done. Otherwise, defenders will overestimate their combat readiness, and attackers will use larger weapon yields than necessary. An accurate method is needed to calculate the most probable number of vehicles remaining upright after a nuclear burst. This report describes one such method. It is essentially the same as that given in another paper,[2] but that reference did not indicate the origins.

[1]*Capabilities of Nuclear Weapons (U), Defense Nuclear Agency DNA EM-1 (July 1972). (SECRET RESTRICTED DATA)*

[2]*Louis J. Belliveau, Analytical Assessment of Damage to Vehicles by Air Blast from Nuclear Weapons--Methodology (U), Harry Diamond Laboratories TR-1838 (December 1977). (CONFIDENTIAL NO FOREIGN DISSEMINATION)*

2. SINGLE VEHICLE OVERTURN

Although the approach is statistical, we start with a single vehicle. Four elements are needed to model overturn: (1) a data base that tabulates the blast parameters involved in overturn, (2) a monotonically changing quantity that describes the variations among vehicles of the same type, and (3) a distribution function that describes these variations in terms of (4) an appropriately chosen blast parameter. Each element is treated separately in this section.

2.1 Data Base

There are no field test data from which an adequate modeling of overturn can be constructed. Many vehicles have never been exposed to a large-yield airburst--nuclear or otherwise. Even for those vehicles for which there is a wide body of data--for example, jeeps--the information is not of the type from which a good distributional model can be constructed. Data, then, must be generated by a good aerodynamic computer code verified, where possible, with field test data.

Such a computer program exists.[3] It has been used to predict the overturn of both wheeled and tracked vehicles. The modeling has been partly verified by results from Dice Throw, a high-yield conventional explosive test. Briefly, the program determines the values of the blast parameters at the maximum ground ranges at which overturn occurs. The values are determined for a variety of yields exploded at altitudes of 60 $W^{1/3}$ m, where W is the yield in kilotons. (Surface bursts also can be treated, but their effects on vehicles differ little from aerial bursts, and we do not concern ourselves with them in this report.) The values of the blast parameters so determined form the data base from whence the distributions are derived (sect. 2.4).

2.2 Variations among Vehicles of Same Type

The basis for any analysis is to exploit the variations among vehicles of the same type. Physical differences exist due to differences in loading and age, but these differences are minute. What is needed is a first-order effect that distinguishes among vehicles of the same type.

The most obvious difference in a battlefield situation is in the relative orientation of the vehicle and the actual ground zero (AGZ) of the weapon. It is easier to turn a vehicle over from the side than

[3] *N. P. Hobbs et al, TRUCK--A Digital Computer Program for Calculating the Response of Army Vehicles to Blast Waves, Kaman AviDyne KA TR-136 (March 1977).*

from the end. Since there is no way to predict the relative orientation between a burst and a given vehicle, the orientation is a random quantity that can be used to distinguish among vehicles of the same type in a given area.

2.3 Distribution Function

Deferring the problem of relating blast parameters and vehicle orientation until section 2.4, we turn our attention to the type of distribution function that should be used. A normal distribution cannot be right, since all blast parameters are positive at overturn. The skew distribution most closely related to the normal function (and most often used in damage calculation) is the lognormal--that is, a distribution that becomes normal if the logarithm of the parameter is used. More precisely, if

$$\Phi(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} e^{-u^2/2}\, du,$$

then the cumulative normal function is given by

$$P\{x\} = \Phi(u)$$

with

$$u = \frac{x - \mu}{\sigma}, \quad -\infty < x < \infty .$$

Here, μ is the mean and σ is the standard deviation. Similarly, the cumulative lognormal function uses

$$u = \frac{\ln x - \ln \xi}{\sigma}, \quad 0 < x < \infty .$$

Here, ξ is the mode and $\mu = \ln \xi$ is the mean.

Finding no good theoretical reason why the lognormal should be used to describe overturn, we must resort to a heuristic argument. Damage is generally well described by a lognormal function if the proper parameter is used. For example, the ill effects of radiation dose on biological specimens can be excellently described by a lognormal function of dose.[4] Also, neutron damage in semiconductors can be described by a lognormal function of fluence, and there appears to be a solid theoretical basis for it.[5] A whole theory of breakage is based on the lognormal distribution.[6] These facts are sufficiently provocative for us to tentatively assume a lognormal distribution and to look for an overturn parameter to fit it.

2.4 Selection of Blast Parameter

The problem resolves, then, into finding a proper blast parameter and somehow using it in a lognormal equation to get a good description of data that relate overturn to the relative vehicle-burst orientation. Sections 2.4.1 to 2.4.4 walk the reader through the step-by-step process by which these goals can be achieved.

2.4.1 Critical Value

It is evident that overturn is a discontinuous process in orientation. No matter what parameter is chosen, there is a value below which the vehicle will not be overturned. At some critical value, the vehicle will just barely be overturned in its most sensitive orientation (usually, within a few degrees of broadside). Designating the parameter by Q and the critical value by k, the argument of the lognormal must then be $Q - k$.

There is an upper limit for overturn sensitivity as well. Beyond some value of Q, the vehicle will be overturned regardless of orientation. In practice, this is an unrealistic limit because the ranges become so small that other effects dominate, such as the crushing of the cab of a wheeled vehicle. The upper limit of the distribution, then, is conveniently taken as infinity, since the small error in probability of overturn thus introduced is masked by other, more serious, damage.

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[4]*Addendum to Personnel Risk and Casualty Criteria for Nuclear Weapons Effects, U.S. Army Nuclear Agency ACN 22744 (March 1976).*

[5]*K. N. Stevens, Neutron Failure Fluence Distribution for Semiconductor Devices, IEEE Annual Conference on Nuclear and Space Radiation Effects, Seattle, WA (July 1972).*

[6]*J. Aitchison and J. Brown, The Lognormal Distribution, Cambridge University Press, United Kingdom (1957), 26-27.*

The quantity $Q - k$ looks innocuous, but it carries serious connotations. By implication, k is independent of yield. This independence certainly seems necessary. If we are to have a parameter or a combination of parameters that describes overturn, it must have its origins in the environment, not in the source of the environment. Further consideration reveals that the effect must be independent of yield regardless of the orientation--that is, that $Q - k = f(\theta)$ at the maximum range at which the vehicle with orientation θ relative to the burst point is overturned. Here, $f(\theta)$ is a function of the orientation only.

We measure θ from the most sensitive orientation. Thus, the zero of θ is at a vector, $\underline{s}$, which is parallel to the earth and points from the center of gravity of the vehicle toward the most sensitive direction--that is, in the direction where $Q = k$ is just sufficient to overturn the vehicle. This geometry is shown in figure 1.

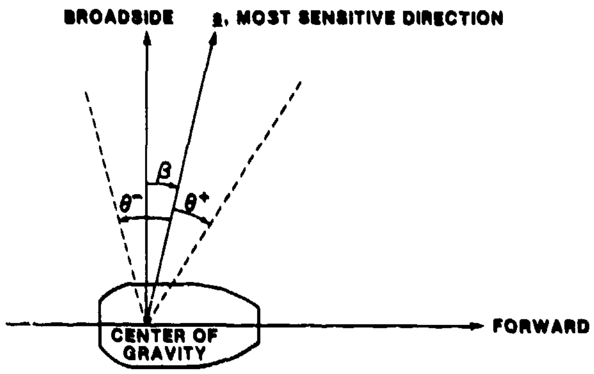

Figure 1. Angular relationships for vehicle overturn.

2.4.2 Effects of Orientation

The concepts of section 2.2 need quantification. Since we cannot predict AGZ, the orientation of vehicles relative to AGZ provides a good way of calculating the probability of overturn. As a simplification, which will be removed later, consider a vehicle to have twofold symmetry--that is, there is not a great difference between the front and the rear of the vehicle. Then the 90-deg angle between side on and end on is all that is necessary to describe all possible orientations.

Measuring the angle as defined in section 2.4.1, let θ increase toward the front of the vehicle. If θ is in degress, then the quantity $P_\theta = \theta/90$ is the probability that the vehicle is oriented between 0 deg and θ. Thus, for angle θ, we determine the minimum value

of $Q - k$ for which overturn occurs and assign the probability P_θ to the cumulative lognormal function for that value of $Q - k$. With several such pairs of values, a least squares fit to a cumulative lognormal function can be performed. For greatest sensitivity, this fit should span the range of values where the cumulative lognormal varies most--that is, in the linear region around the mean. This mean (where $P_\theta = 0.5$) is at the $\theta = 45$-deg orientation that many references call "random."

Unfortunately, few vehicles have front and rear symmetry. However, all that we have studied so far exhibit bilateral symmetry. We therefore define θ^+ and θ^- as in figure 1, with the positive sign measuring θ from $\underline{s}$ forward and the negative sign measuring θ from $\underline{s}$ rearward. If β is the angle that $\underline{s}$ makes with the broadside direction,

$$P_\theta^- = \frac{\theta^-}{90 + \beta} \quad \text{and} \quad P_\theta^+ = \frac{\theta^+}{90 - \beta} .$$

These corrections are often nontrivial. We can then determine two lognormal distributions--one forward and one rearward. For simple treatments, the means and the sigmas can be averaged and the 90-deg model can be used. We will see that this is a reasonable approximation for most vehicles. However, not much effort is involved to include both directions in a computer program.

2.4.3 Blast Parameter

Aerodynamic computer runs can be made for a variety of angles and yields. For each angle and yield, there is a ground range at which the vehicle is just barely overturned. The common blast parameters (peak static and peak dynamic overpressures and their corresponding impulses) can be computed at these ranges.[7] If they are computed, it becomes apparent that these quantities depend on yield for a given angle. At the suggestion of L. J. Belliveau of the Harry Diamond Laboratories, the product of the peak overpressure, Δp, and the dynamic impulse, I_q, was investigated. For yields above about 10 kT, we found that $\Delta p I_q$ hardly depends on yield at overturn ranges for all vehicle types investigated so far. Accordingly, $\Delta p I_q - k$ became a candidate for the desired parameter.

[7] *William E. Sweeney, Jr., Cyrus G. Moazed, and John S. Wicklund, Nuclear Weapons Environments for Vulnerability Assessments to Support Tactical Nuclear Warfare Studies (U), Harry Diamond Laboratories TM-77-4 (June 1977). (CONFIDENTIAL)*

Two corroborative threads also support the use of $\Delta pI_q - k$. Sweeney et al[7] give formulas for both Δp and I_q. When we combine them, we obtain

$$\Delta pI_q = AW^B r^C \ , \tag{1}$$

with $A = 1.587 \times 10^{-2}$, $B = 1.711$, and $C = -4.133$. The range, r, is in kilometers and the yield, W, is in kilotons. At the critical range, r_c (the maximum range at which overturn occurs), $\Delta pI_q = k$. Then

$$r_c = \left(\frac{0.0159}{k}\right)^{0.242} W^{0.414} \ . \tag{2}$$

Equation (2) is of interest because a large number of range-yield data plots from the 1880's to the present time indicate that blast damage goes approximately as the 0.4 power of the yield. In fact, DNA EM-1 gives[1] the same exponent as equation (2), namely, 0.414.

Equation (2) is a simplification of a more general form. If we let $x = \ln(\Delta pI_q - k) - \ln \xi$, we find $\Delta pI_q = k + \xi e^x$, from which

$$r_x = \left(\frac{0.0159}{k + e^x}\right)^{0.242} W^{0.414} \ . \tag{3}$$

Equation (3) elaborates upon the assumptions. As θ varies from 0 deg to end on, x varies from $-\infty$ to $+\infty$. The errors at the high end discussed in section 2.4.1 are then seen to be relatively minor, since the exponential soon dominates. Also of interest in equation (3) is the value at $x = 0$, corresponding to 45 deg. Though frequently used to describe a "random" orientation, the value at $x = 0$ can lead to gross errors in calculating range.

The second corroborative thread for the use of $\Delta pI_q - k$ as the overturn parameter is its excellent fit to a lognormal distribution for a wide variety of vehicles. This fit is demonstrated in the sequence of tables I to III. Table I lists computer results for a variety of vehicles. The angle refers to a line drawn through the center of gravity and normal to the side of the vehicle (broadside).

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[1]*Capabilities of Nuclear Weapons (U), Defense Nuclear Agency DNA EM-1 (July 1972). (SECRET RESTRICTED DATA)*

[7]*William E. Sweeney, Jr., Cyrus G. Moazed, and John S. Wicklund, Nuclear Weapons Environments for Vulnerability Assessments to Support Tactical Nuclear Warfare Studies (U), Harry Diamond Laboratories TM-77-4 (June 1977). (CONFIDENTIAL)*

The values in the table are the average values of ΔpI_q at which the vehicles are overturned at the indicated angles. These averages result from computer runs at yields of 10, 40, and 100 kT: ΔpI_q at overturn is relatively independent of yield.

TABLE I. VALUES OF ΔpI_q FOR OVERTURN AT VARIOUS ANGLES

Vehicle	Angle (deg)								
	-60	-45	-30	-15	0	15	30	45	60
M113A1 (full)	21.52	13.64	11.09	9.74	8.88	9.82	10.79	14.14	23.56
M113A1 (empty)	16.13	10.87	8.20	7.36	6.84	7.25	8.25	10.80	17.10
M548 (full)	31.03	18.65	14.95	12.87	11.86	11.87	12.95	15.01	18.01
M548 (empty)	7.22	5.76	5.28	4.80	4.77	5.11	5.84	7.60	13.20
M163 VADS	19.47	12.55	9.89	8.78	8.36	8.68	9.96	12.78	20.47
M125A1	22.56	14.83	11.43	10.05	9.16	10.08	11.36	14.99	23.63
M106A1	25.37	16.40	12.91	11.49	10.54	11.32	12.90	17.02	26.61
ZSU	51.39	32.81	25.65	23.32	22.86	22.94	24.76	31.30	50.43
M752	8.89	5.60	4.23	3.84	3.60	3.71	4.03	5.16	8.01
M688E1	10.43	6.34	4.97	4.52	4.34	4.29	4.79	6.13	9.33
M35A2/S280	0.977	0.612	0.513	0.478	0.481	0.517	0.545	0.715	1.129

Note: Angle of 0 deg is exact broadside. Negative and positive angles denote rear and forward quadrants, respectively.

Table II was derived from table I. A spline fit was applied to determine the angle β; k is the value of the smoothed function at that point, not very different from the 0-deg value in table I. The means and the sigmas of the rearward and forward cumulative lognormal functions are indicated in table II by the negative and positive signs, respectively. These were determined by least squares fits to the appropriate data. The last two columns in table II are average means and sigmas that represent least squares cumulative lognormal fits to all the data.

TABLE II. SUMMARY OF CONSTANTS FOR VARIOUS VEHICLES

Vehicle	β (deg)	k	Lognormal distribution value					
			Rearward		Forward		Average	
			μ^-	σ^-	μ^+	σ^+	$\bar{\mu}$	$\bar{\sigma}$
M113A1 (full)	-0.8	8.88	1.69	1.89	1.70	2.06	1.69	1.98
M113A1 (empty)	+1.3	6.83	1.29	2.15	1.40	2.24	1.34	2.20
M548 (full)	+7.6	11.74	1.79	2.27	1.31	2.39	1.60	2.55
M548 (empty)	-7.2	4.72	0.325	2.08	0.870	2.47	0.667	2.41
M163 VADS	+2.3	8.35	1.35	2.38	1.56	2.40	1.46	2.39
M125A1	-0.2	9.16	1.74	1.95	1.76	2.01	1.75	1.98
M106A1	+0.7	10.54	1.78	2.00	1.86	2.15	1.82	2.08
ZSU	+7.9	22.78	1.85	3.25	2.42	3.05	2.12	3.06
M752	+2.0	3.59	0.598	2.32	0.458	2.52	0.532	2.47
M688E1	+10.9	4.26	0.360	2.71	1.02	2.88	0.646	2.73
M35A2/S280	-8.5	0.474	-1.60	2.69	-1.70	2.40	-1.66	2.60

Note: β is the angle of the minimum as measured from broadside. Negative values are rearward; positive are forward. k is the critical value; μ is the mean; σ is the standard deviation.

Table III shows the goodness of fit by comparing the observed values with those calculated from the lognormal distributions. The P_i^- are the various values of P_θ^- and the P_i^+ are the various values of P_θ^+. The calculated values are obtained from the cumulative lognormal functions using μ^-, σ^-, and μ^+, σ^+. Calculations were made also by using $\bar{\mu}$ and $\bar{\sigma}$; values in parentheses are those that differed from the ones obtained through μ^-, σ^-, or μ^+, σ^+.

The errors in table III are quite small. A reader unfamiliar with probability calculations might be helped by the following example. One of the largest differences occurs in the forward direction for the M688E1, with an observed value of 0.43 and a calculated value of 0.50 when $\bar{\mu}$ and $\bar{\sigma}$ are used (P_3^+ in table III). Assume that we have a coin weighted so that there is a probability of 0.43 of the head showing when the coin is tossed. (A fair coin exhibits a probability of 0.50.) Then detecting the weighted coin with a confidence of 95 percent would

TABLE III. GOODNESS OF FIT USING ΔPI_q AS OVERTURN PARAMETER

Vehicle	Method	Overturn probability							
		P_4^-	P_3^-	P_2^-	P_1^-	P_1^+	P_2^+	P_3^+	P_4^+
M113A1 (full)	Observed	0.66	0.49	0.32	0.16	0.17	0.34	0.50	0.67
	Calculated	0.67 (0.66)	0.47	0.32	0.17 (0.18)	0.20 (0.19)	0.30	0.49	0.68 (0.69)
M113A1 (empty)	Observed	0.67	0.51	0.34	0.18	0.15	0.32	0.49	0.66
	Calculated	0.67 (0.66)	0.52 (0.51)	0.32	0.18	0.16	0.32	0.50 (0.51)	0.66 (0.67)
M548 (full)	Observed	0.69	0.54	0.38	0.23	0.09	0.27	0.45	0.64
	Calculated	0.70	0.53 (0.55)	0.39 (0.43)	0.23 (0.28)	0.08	0.32 (0.29)	0.48 (0.44)	0.59 (0.54)
M548 (empty)	Observed	0.64	0.46	0.28	0.09	0.23	0.38	0.54	0.65
	Calculated	0.61 (0.54)	0.44 (0.40)	0.33 (0.30)	0.08 (0.09)	0.23 (0.25)	0.38 (0.41)	0.53 (0.56)	0.70 (0.73)
M163 VADS	Observed	0.68	0.51	0.35	0.19	0.14	0.32	0.49	0.66
	Calculated	0.67 (0.66)	0.52 (0.50)	0.35 (0.34)	0.19 (0.18)	0.14 (0.15)	0.33 (0.34)	0.49 (0.51)	0.65 (0.67)
M125A1	Observed	0.67	0.50	0.33	0.16	0.17	0.34	0.50	0.67
	Calculated	0.67 (0.66)	0.50	0.32	0.17	0.18	0.31	0.50	0.68
M106A1	Observed	0.67	0.50	0.34	0.17	0.16	0.33	0.50	0.66
	Calculated	0.68 (0.66)	0.50 (0.49)	0.32	0.18	0.16	0.32	0.50 (0.51)	0.66 (0.68)
ZSU	Observed	0.69	0.54	0.39	0.23	0.09	0.27	0.45	0.64
	Calculated	0.68 (0.66)	0.56 (0.52)	0.40 (0.36)	0.22 (0.19)	0.08 (0.10)	0.28 (0.32)	0.46 (0.50)	0.62 (0.65)
M752	Observed	0.67	0.51	0.35	0.18	0.15	0.32	0.49	0.66
	Calculated	0.68	0.52 (0.53)	0.32 (0.34)	0.20 (0.22)	0.15 (0.14)	0.30 (0.29)	0.50 (0.49)	0.66 (0.65)
M688E1	Observed	0.70	0.55	0.40	0.26	0.05	0.24	0.43	0.62
	Calculated	0.70 (0.67)	0.55 (0.51)	0.40 (0.36)	0.26 (0.23)	0.05	0.28 (0.32)	0.44 (0.50)	0.58 (0.64)
M35A2/S280	Observed	0.63	0.45	0.26	0.08	0.24	0.39	0.54	0.70
	Calculated	0.63 (0.65)	0.44 (0.45)	0.27	0.08	0.27 (0.28)	0.34 (0.35)	0.54	0.70 (0.68)

Note: Parentheses denote all values calculated by using $\bar{\mu}$ and $\bar{\sigma}$ that differ from those calculated by using the more precise parameters.

require 780 tosses; for a confidence of 99 percent, 1350 tosses would be required. Thus, even the largest differences are not particularly bad. Other functional forms like $\Delta p^a I_q^b$ (a and b are constants) have been tried without nearly so good results.

Various vehicles have been treated. Table I lists mostly tracked vehicles. Wheeled vehicles have been treated somewhat differently by Belliveau.[2] The M35A2 with the S280 shelter is included in table I because the results differ significantly from those reported by Belliveau,[2] which uses a simple, one-degree-of-freedom computer program. TRUCK seems better because it has been partially verified in high-yield conventional tests. Also of interest is the Russian ZSU: it appears to fit the scheme as well as U.S. vehicles. The ZSU was modeled by using the data[8] in Jane's Weapon Systems 1977.

The entries in table II permit intercomparison of relative vulnerabilities of vehicles. The larger the value of k is, the more difficult it is to overturn the vehicle. With one exception, high k correlates with high $\bar{\mu}$. This correlation is to be expected, for if it is difficult to overturn a vehicle from the side, it should be proportionately more difficult to overturn it from any other angle. The one exception seems to be the M548 (full), but closer examination shows that this exception is possibly due to the large asymmetry. The value of $\bar{\sigma}$ is one of the largest, indicating that the distribution is not sharply peaked.

The quantity $\Delta p I_q$ necessary to just overturn tracked vehicles depends on yield for yields less than 10 kT and increases sharply as the yield decreases, as seems intuitively correct. Below some yield, the blast duration is so short that inertia keeps the vehicle from overturning. Wheeled vehicles are more easily overturned, as can be seen by the k values by Belliveau.[2] Accordingly, yield independence is observed down to about 1 kT.

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[2] *Louis J. Belliveau, Analytical Assessment of Damage to Vehicles by Air Blast from Nuclear Weapons--Methodology (U), Harry Diamond Laboratories TR-1338 (December 1977). (CONFIDENTIAL NO FOREIGN DISSEMINATION)*

[3] *N. P. Hobbs et al, TRUCK--A Digital Computer Program for Calculating the Response of Army Vehicles to Blast Waves, Kaman AviDyne KA TR-136 (March 1977).*

[8] *R. T. Pretty, ed., Jane's Weapon Systems 1977, Jane's Yearbooks (1977), 92-93.*

2.4.4 Vehicular Asymmetries

Figures 2 to 12 show that no vehicle is perfectly symmetric. Conversion from ΔpI_q-space to distance was done by using the formulas by Sweeney et al.[7] A value of range was taken and the value of $\Delta pI_q - k$ was calculated for each yield. This value of $\Delta pI_q - k$ was made the argument in the cumulative lognormal function and the probability was calculated. The curves terminate abruptly at the range given by equation (2); beyond this point, the vehicle is not overturned, regardless of orientation.

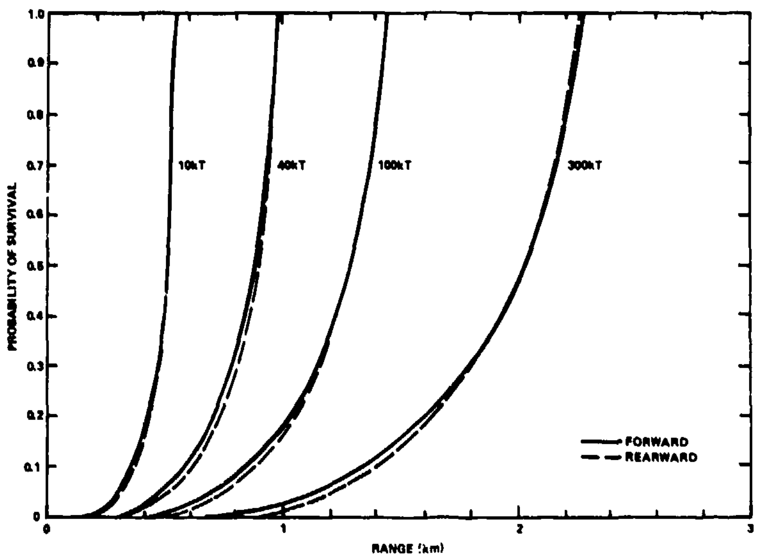

Figure 2. Survival probabilities for M113A1 (full).

The asymmetries do not change the survival probabilities, with a few exceptions. Of interest is the large change in "polarity" of the M548 occasioned by the shift of the center of gravity between the loaded and empty states. Figure 12 has a different scale from the others, illustrating the greater vulnerability of a wheeled vehicle to overturn, expecially if it is equipped with the large "sail" area of an S280 communications shelter.

[7] *William E. Sweeney, Jr., Cyrus G. Moazed, and John S. Wicklund, Nuclear Weapons Environments for Vulnerability Assessments to Support Tactical Nuclear Warfare Studies (U), Harry Diamond Laboratories TM-77-4 (June 1977). (CONFIDENTIAL)*

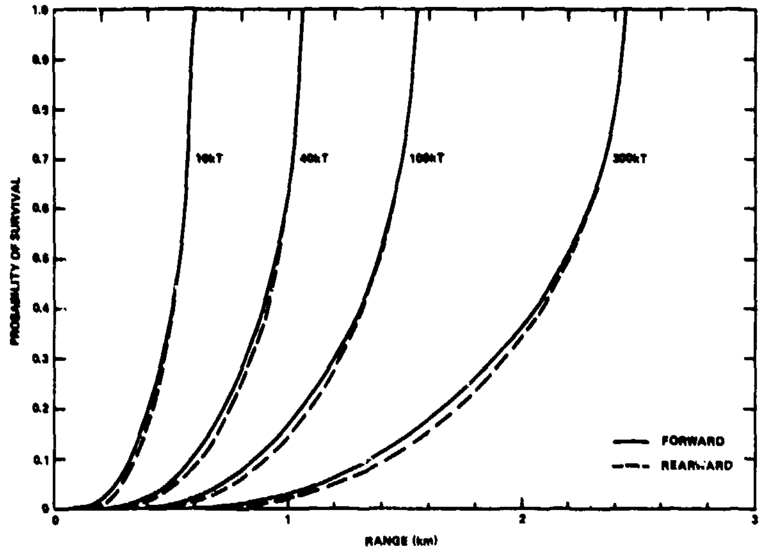

Figure 3. Survival probabilities for M113A1 (empty).

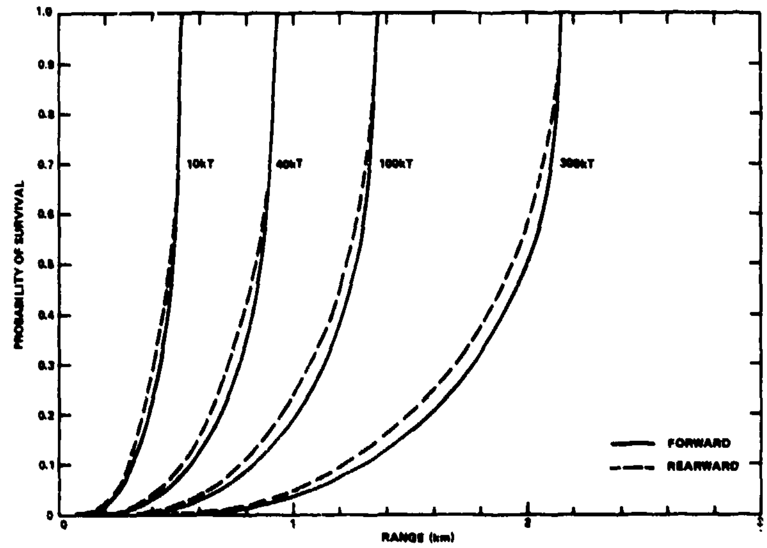

Figure 4. Survival probabilities for M548 (full).

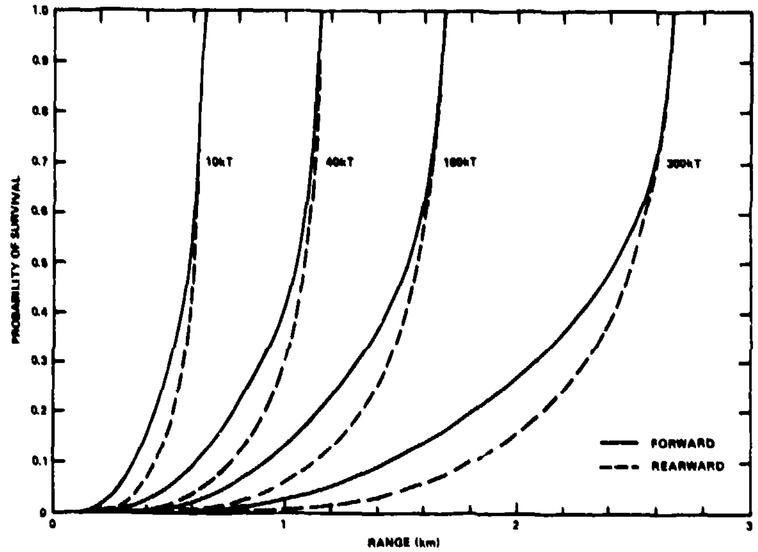

Figure 5. Survival probabilities for M548 (empty).

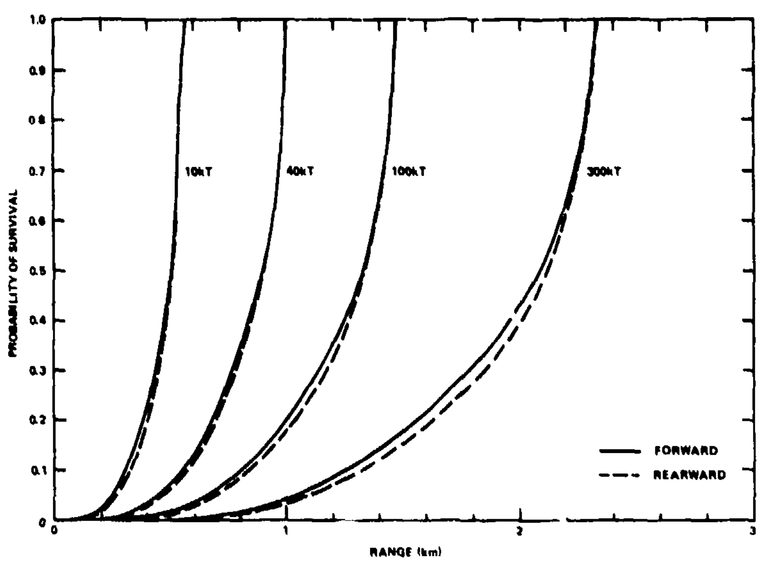

Figure 6. Survival probabilities for M163 VADS.

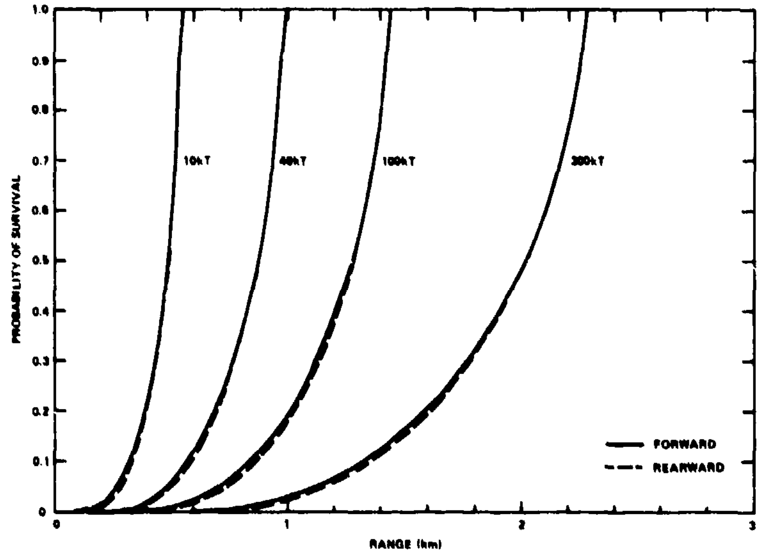

Figure 7. Survival probabilities for M125A1.

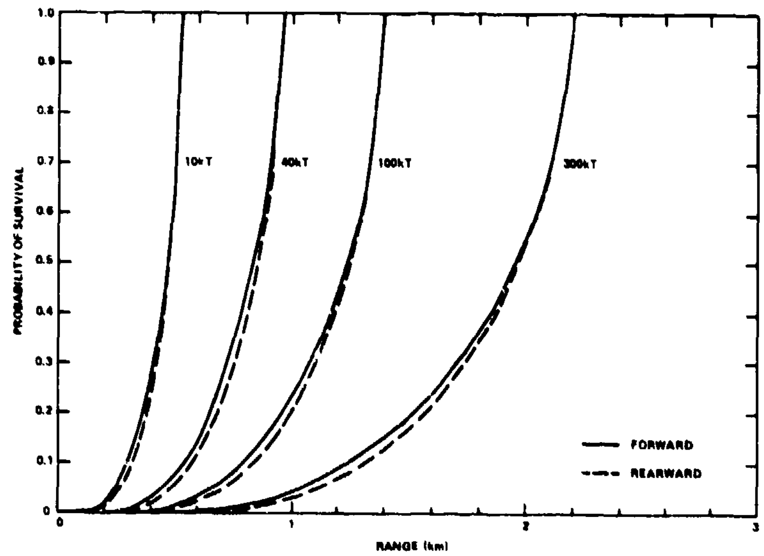

Figure 8. Survival probabilities for M106A1.

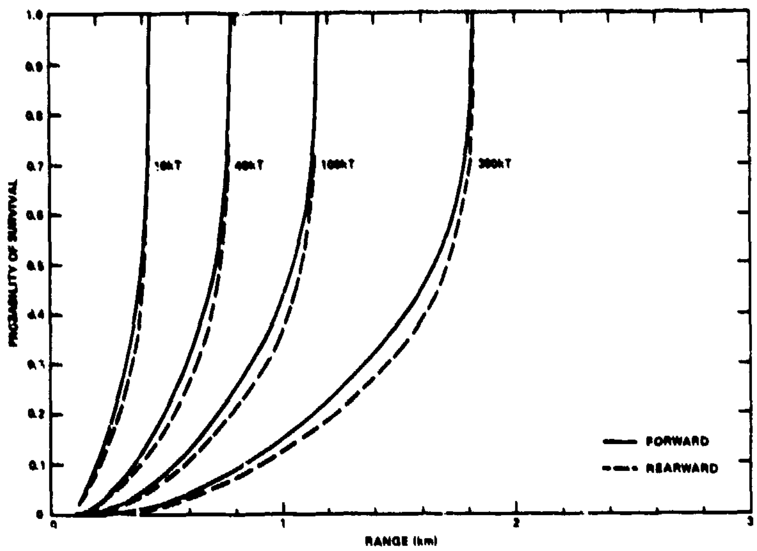

Figure 9. Survival probabilities for ZSU.

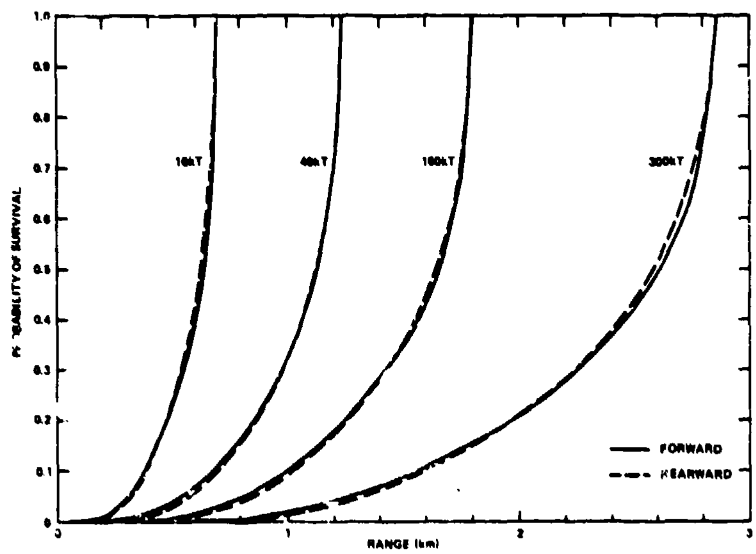

Figure 10. Survival probabilities for M752.

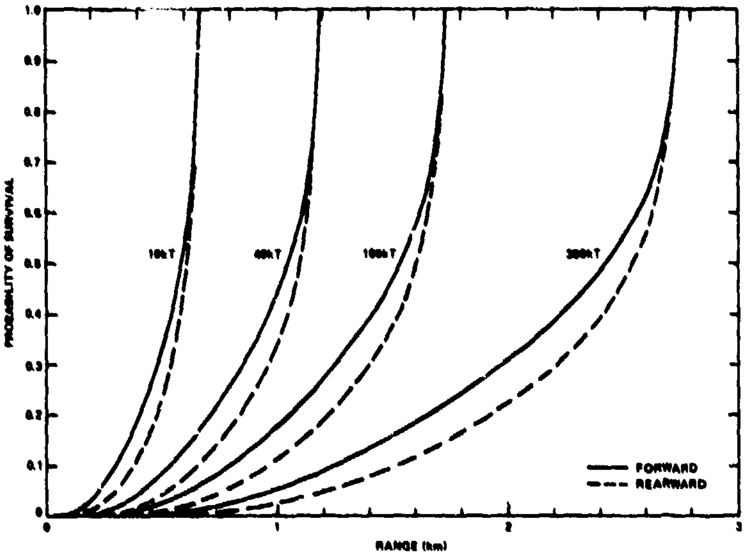

Figure 11. Survival probabilities for M688E1.

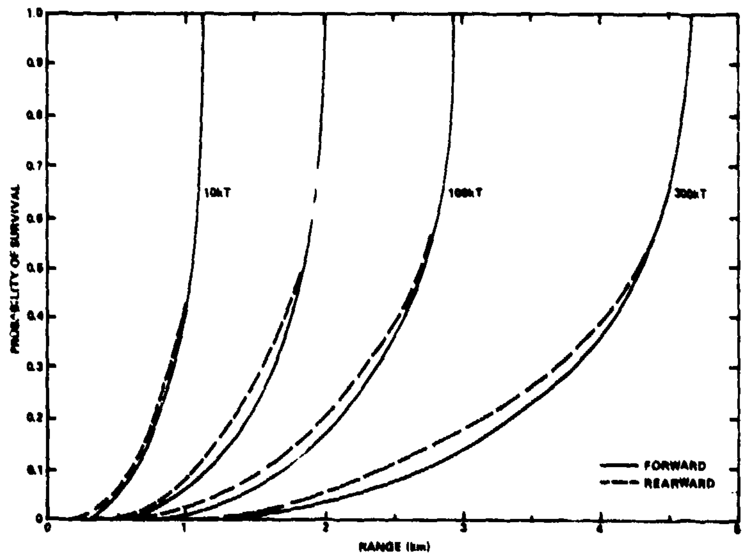

Figure 12. Survival probabilities for M35A2/S280.

3. ARRAYS OF VEHICLES

Except for those which load or transport nuclear weapons, single vehicles are not significant targets in nuclear warfare. Clusters of vehicles attached to military units are frequently bonus targets. For example, a nuclear-capable howitzer battery may be a prime target, and overturn of its M113A1 cargo carriers might well cripple the unit even if the actual ground zero is too removed to damage the artillery pieces. Other vehicle clusters, such as armored or mechanized infantry units massed for assault or on line for defense, would surely be targets of opportunity or intent.

In principle, perhaps, vehicles on a battlefield should be randomly arrayed, but they rarely are. Armor organizes along a line. All pieces in an artillery battery usually point in the same direction, so the cargo carriers that supply their ammunition are drawn up for the most convenient loading. Vehicles in a staging area are parked so that they can be moved out rapidly. Road marches are highly orientated linear arrays. In short, there are few opportunities for randomly aligning vehicles on the battlefield. Still, for completeness, we treat both random and ordered alignments. It is assumed throughout this paper that the vehicles are dispersed widely enough for the effects to be independent and that they are on smooth terrain.

3.1 Randomly Aligned Clusters of Vehicles

The method of treating randomly aligned clusters of vehicles is the same as that described by Spyropoulos and Wicklund.[9] It is assumed that the positions of the vehicles are known, but their individual orientations relative to the burst are completely unknown. This is not as paradoxical as it seems at first. A unit occupies a more or less standard area and the mission of the unit calls for the vehicles to be located at certain places within that area. Orientation is a matter of convenience or is deliberately randomized, so it cannot be as well known as the most probable location.

The situation is shown schematically in figure 13, except that the orientations of the vehicles are completely unknown. A point, VC, is taken near the center of the array and a convenient reference line is drawn. Another line from VC is drawn at some angle, α. Let a nuclear weapon of a given yield be detonated at a point along this line. With

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[9] *Chris E. Spyropoulos and John S. Wicklund, A Method for Assessing the Vulnerability of Small Units in Tactical Nuclear Engagements (U), Harry Diamond Laboratories TR-1851 (June 1978). (CONFIDENTIAL)*

the formulas of Sweeney et al[7] and the tabulated k value, the overturn parameter $\Delta pI_q - k$ can be calculated. By using $\bar{\mu}$ and $\bar{\sigma}$, the probability of survival of each vehicle can be calculated, and the average survival probability of the array can be obtained from

$$P = \frac{1}{N} \sum_{1}^{N} P_i \ , \qquad (4)$$

where N is the number of vehicles and the P_i are the individual survival probabilities.

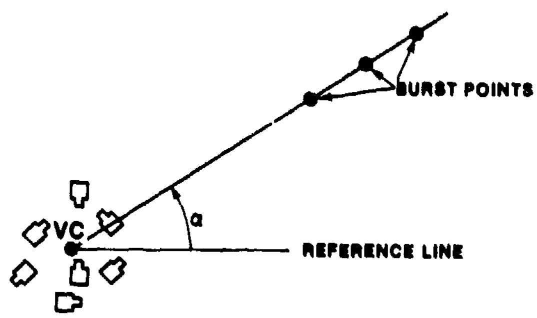

Figure 13. Schematic cluster of vehicles.

Angle α is then changed and the process is repeated until the array has been surrounded. We have found that azimuthal variations can be made negligible by properly locating VC. This relocation can be done iteratively. The critical point is called the "vulnerability center." A practical limit is reached when the major dimension of the array approaches the extent of the effect for that yield: for 1 kT, the major dimension should not exceed about 0.3 km. For each yield, various burst points along the line from VC are taken so that about 10 ranges with $0.1 \leq P \leq 0.9$ are obtained.

[7] *William E. Sweeney, Jr., Cyrus G. Moazed, and John S. Wicklund, Nuclear Weapons Environments for Vulnerability Assessments to Support Tactical Nuclear Warfare Studies (U), Harry Diamond Laboratories TM-77-4 (June 1977). (CONFIDENTIAL)*

The entire procedure is repeated with different yields. Although the ranges must be changed, the values of ΔpI_q at VC are virtually the same for equal survival probabilities. The only differences due to yield are in the magnitude of the (negligible) azimuthal variations: the larger the yield, the greater the range, the better the point approximation, and the more negligible the variations.

This method thus reduces the array to a point target with a variation in survival probability as a function of ΔpI_q at the vulnerability center. It has proved possible to describe random arrays of vehicles similarly to describing individual vehicles, namely, in terms of $\Delta pI_q - k$. A value for k is obtained by finding the range where P in equation (4) becomes just less than 1.00 and then computing ΔpI_q at VC. Again, excellent fits to cumulative lognormals are obtained. Treatments of some vehicular arrays are detailed by Spyropoulos and Wicklund.[9] Clusters of different vehicle types inside a military unit position should each be treated separately.

It is important to see the essential difference between the single vehicle and the random array. The *form* $\Delta pI_q - k$ is the same, but the distribution for single vehicles exploits the azimuthal asymmetry, which is explicitly eliminated for the random array. (It may be possible to take the geometric center of the array and to use the asymmetry in the same way as for individual vehicles.)

3.2 Aligned Clusters of Vehicles

The term "aligned" is used here to denote that the orientation of each vehicle is known, even though these orientations might be random. More exact estimates can be made for aligned clusters (sect. 3.2.1) and for highly ordered arrays of vehicles, such as found in road marches (sect. 3.2.2).

3.2.1 Aggregated Assessment

Since the orientation of the vehicle is known, a different assessment method is possible. Given the point of detonation, the angle between AGZ and the vector, $\underline{s}$, is known. The distribution function for the vehicle in question can then be solved backwards to get the value of ΔpI_q necessary to overturn the vehicle at that angle. If this value is less than ΔpI_q computed from equation (1), the vehicle is overturned. Thus, an actual vehicle count can be obtained.

If the array is not highly ordered or, if ordered, is sufficiently small, a vulnerability center can be obtained by a method similar to that in section 3.1, but by using the actual fraction of

[9] *Chris E. Spyropoulos and John S. Wicklund, A Method for Assessing the Vulnerability of Small Units in Tactical Nuclear Engagements (U), Harry Diamond Laboratories TR-1851 (June 1978). (CONFIDENTIAL)*

vehicles overturned. For several vehicles, at least, this method intuitively seems more accurate. (I am currently comparing the two methods.)

3.2.2 Highly Ordered Arrays of Vehicles

It is patently wrong to treat a highly ordered array of vehicles such as a road march by defining a vulnerability center: the unit is simply too strung out and too directional. Spyropoulos and Wicklund[9] show that a road march can be conveniently represented by three vulnerability centers for nondirectional effects like radiation dose to personnel, but such a representation is clearly incorrect for vehicle overturn. (I am studying the possibility that a highly ordered array of vehicles can itself be treated in the same way as a single vehicle.)

3.3 Terrain Irregularities

This analysis is "table top" in the sense that terrain irregularities have not been considered. Such features can modify the shock wave and tilt the vehicles off the dead level that was assumed for this study. Shock-wave modification might be handled by a trick like defining an azimuthally dependent effective yield. Initial tilt of the vehicles, however, introduces a complication that cannot be treated in the simple way discussed in this paper.

[9] *Chris E. Spyropoulos and John S. Wicklund, A Method for Assessing the Vulnerability of Small Units in Tactical Nuclear Engagements (U), Harry Diamond Laboratories TR-1851 (June 1978). (CONFIDENTIAL)*

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